Path-tracing Approach for Solar Radiation Modeling in CFD

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Abstract

In this paper we are presenting a novel approach for the solar radiation modelling in CFD, based on the path-tracing principle. In this modelling approach a specified number of beams (carrying along specified amount of heat) are released from the given direction, passing through the numerical domain and interacting with the surrounding media. Thus the absorption, refraction and reflection when changing media (including multiple reflections) are accounted for, together with the heat exchange on the hitting surfaces. In this way the totality of solar radiation effects (e.g. lighting, shading and solar heating) can be introduced into a CFD simulation, without a significant increase in the computational demand or difficulties with the stability of the numerical calculation. The performance of this novel approach is shown in the example of predicting solar heating of a realistic room.

1. Introduction

Computational Fluid Dynamics (CFD) became very powerful engineering tool for the analysis of indoor flow characteristics, as it can provide detailed spatial and temporal (in case of transient flows) distribution of all flow quantities relevant for the analysis (e.g. temperature, velocity, species). The transport phenomena of importance for indoor flows (e.g. turbulence, thermal effects, influence of passive scalars, etc.) are in CFD accounted for by solving appropriate set of transport equations. However, the inclusion of solar radiation effects in CFD indoor simulations is one of the weak points, because they cannot be modelled through a transport equation due to their non-locality.

The solar radiation modelling approach presented here is not subjected to restrictive geometrical constrains nor it is based on physical assumptions and simplifications, unlike the radiation models typically used in the most of the commercial CFD codes (e.g. *S2S* or *P1*). In the present modelling approach the radiation beams (in this case solar beams are analyzed) are followed as they are passing the numerical domain, interacting thus with the surrounding media or the hitting surfaces. This interaction includes the energy transfer, as well as the frequency dependent effects. In order to test the performance of this radiation modelling approach coupled with CFD, the solar heating of a realistic room was calculated, with the obtained heat fluxes, temperature distribution and the corresponding air velocity inside the room.

In the following sections this path-tracing modelling approach is described, followed by the simulation setup for solar heating of a room and the obtained results. Finally, some conclusions and discussion about the presented radiation modelling are concluding this paper.

2. Path-tracing Radiation Modelling

In most of the available CFD codes, radiation is treated as weak effect, where huge simplifications can be performed influencing the accuracy accordingly. Several specific algorithms were developed, based on an assumption of the radiation field: e.g. the P1 model considers the volumes as perfectly scattering, while the S2S neglects volumetric effects and directed reflection [1]. For many purposes these models can be useful, but for the solar radiation they are not adequate. If the radiation is considered as mayor effect, like in the illumination simulations, different approaches are necessary, and the *path-tracing* [2] is one of the advanced methods to be used. Opposed to the more common *ray-tracing*, volumetric emission, scattering and absorption are considered. While in normal illumination applications only the surface triangulation is created, in three-dimensional CFD already a volumetric mesh is required.

Both with ray-tracing and path-tracing methods, so called *light-rays* are cast from specified sources [3]. These light-rays represent an infinitesimal solid angle of the wave-front. By following the physical path of a large number of these rays through the geometry, the radiation equation can be solved [4]. As a demonstration of this principle, the solar irradiation of a room is presented in Fig.1. The typical error in this approach scales with the number of rays N in the order of $O(1/N^{0.5})$. Faster convergence can be achieved by replacing this numerical integration by a *Monte-Carlo* approach, together with importance sampling, leading to the approximate $O(1/N^{1,5})$ that is achieved by the used implementation. When applied to light-rays, this translates into all rays carrying the same intensity, but casting more rays from bright surfaces or in preferred directions. Additionally, one can treat these rays carrying several intensities to calculate spectral effects in colour and infrared bands. Most computational effort is used for the path-finding, and hence there is only little overhead for spectral calculations.

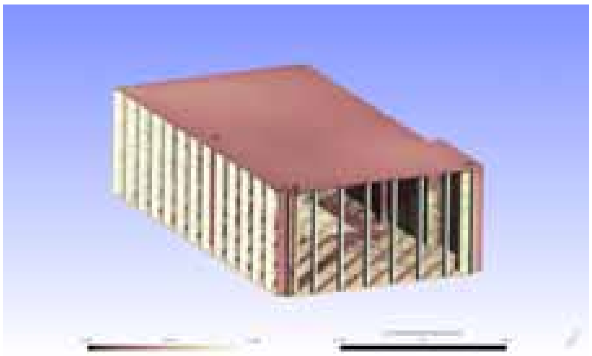

Figure 1: individual path-traced beams (black lines: diffuse reflection paths and the incoming parallel beams) viewed side-wards in the considered test room, showing the coupling between CFD and volumetric path-tracing.

This path-tracing method was successfully coupled to a CFD code, so that the effectiveness of this approach is compared with other common radiation models, and the advantages in computational effort and accuracy are demonstrated [5]. To respect the different material parameters of the low-e glass windows, path-tracing can respect the spectral transparencies, spectral absorption in the glass, reflection losses, shadowing, and the comparably trivial diffuse reflection in the room itself. Furthermore, also secondary heat radiation can be considered easily, as the in-house developed code is bi-directionally coupled with the fluid dynamics simulations' thermal field.

3. Simulation Setup

In order to test the performance of the presented solar radiation modelling approach, the simulation of a realistic room heated by solar radiation is performed. The geometry and construction of the simulated room, together with all façade characteristics and material properties, are assumed following the test room of *HANS HÖLLWART Forschungszentrum für integrales Bauwesen AG* (FIBAG), as a part of the *Multi-functional Plug-and-Play Façades* (MPPF) project [6]. The difference with the real test room is that no ventilation is assumed in the simulated room, and the simulation domain includes a table.

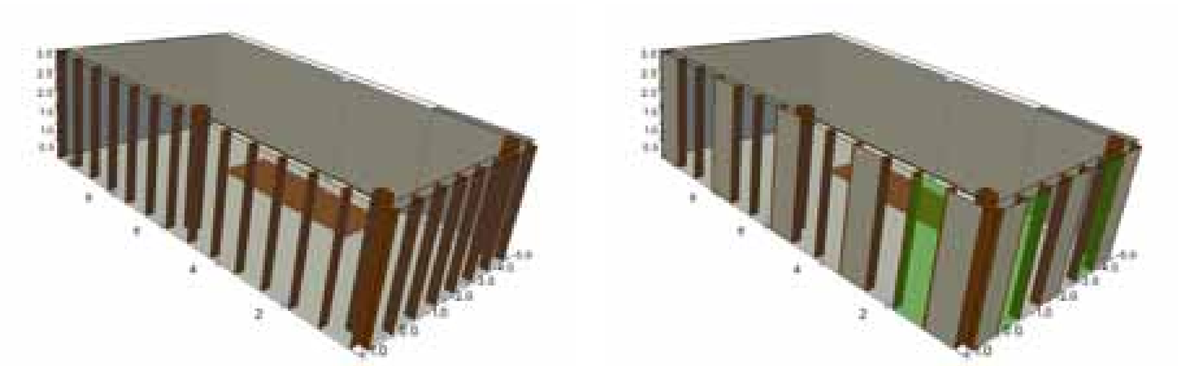

Figure 2: the geometry of the simulated test room and the construction of the façade (brown – metal frame; fully transparent – glass; grey – opaque surface/HVAC element; green – semi-transparent surface/PV element), for the basic façade configuration (left) and the modified façade configuration (right).

Presented in Fig.2 are two configurations of the test room that are investigated, with the difference in their façade configuration. In the basic configuration (left) the entire room façade is made of double glass and the related construction frame, whereas in the modified configuration (right) the design of the advanced façade includes the HVAC and PV elements mounted in the construction frame.

In the simulation of both configurations, the solar radiation was modelled using path-tracing approach [5], with *10.000.000* light-rays released, the solar heat flux set to $1000\ W/m^2$, and 60^o taken as the sun direction. The volumetrically absorbing solar radiation was assumed for the glass of all windows, with the effective *U-value* of *0.55*. As for the HVAC elements, they are assumed to be fully absorbing and opaque, whereas two PV elements are semi-transparent (with *10%* and *20%* transparency). The façade frame construction is also assumed to be fully absorbing and opaque, and the arrangement of the elements in both façade configurations is presented in Fig.2. The walls and the ceiling of the room were treated for radiation as black bodies, whereas the floor and the table were assumed to be grey. The reflection inside the test room was assumed as diffuse.

The heating of room walls by solar radiation induced circulating indoor flow due to the natural convection. For the simulation of the flow and thermal field, the commercial CFD package *FLUENT* [7] was used. For all solid boundaries no-slip condition was applied for momentum, and the convective heat flux for the thermal equation ($2\ W/m^2$ heat transfer coefficient). The solar heating contribution (obtained from the separate, solar path-tracing calculation) was inserted directly into the thermal equation as the source term. The effects of turbulence were modelled with k-ε *RNG* model, and the Bousinesq approximation was used for buoyancy effects (*0.0035 1/K* expansion coefficient).

4. Results

The comparison between the results obtained for the solar heating of the test room with two façade configurations, shown in the following figures, presents the ability of the path-tracing approach to account for all effects of importance for the solar heating of a room. The solution provided the spatial distribution of the solar irradiation inside the room, for the specified boundary conditions, and the related fluid flow characteristics. On the solar irradiation pattern (Fig.3) one can recognize shadows of the façade frame (with related elements for the modified configuration), the shadow of the table, and the light spot on the inner vertical walls coming from the sun light that enters through the façade.

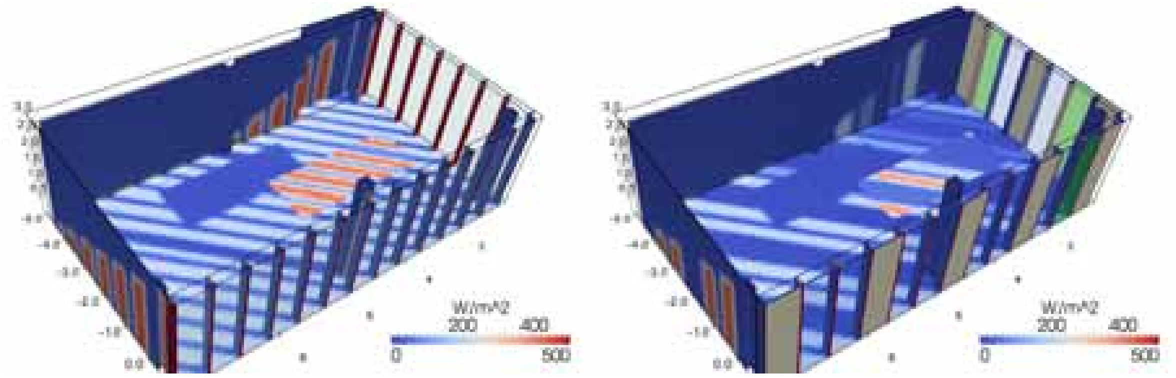

Figure 3: the heat flux from the solar radiation at the floor and the inside walls of the testing room, with the basic façade configuration (left) and the modified façade configuration (right). Façade configuration: brown – metal frame; fully transparent – glass; grey – opaque HVAC element; green – semi-transparent PV element.

As shown in Fig.4, the temperature distribution over the room walls, as well as the temperature of the table, follows the imprint of the established solar irradiation pattern, together with the flow pattern induced by natural convection. Namely, the parts of vertical walls closer to the façade are irradiated the strongest, and as they absorb the heat their temperature increases. The natural convection is thus initiated, with the up-flow over the inner walls and the down-flow over the façade. Therefore relatively warmer region is found around corners of inner walls, and relatively colder region is found around the corners of the outer walls. Very different temperatures are obtained for different façade configurations.

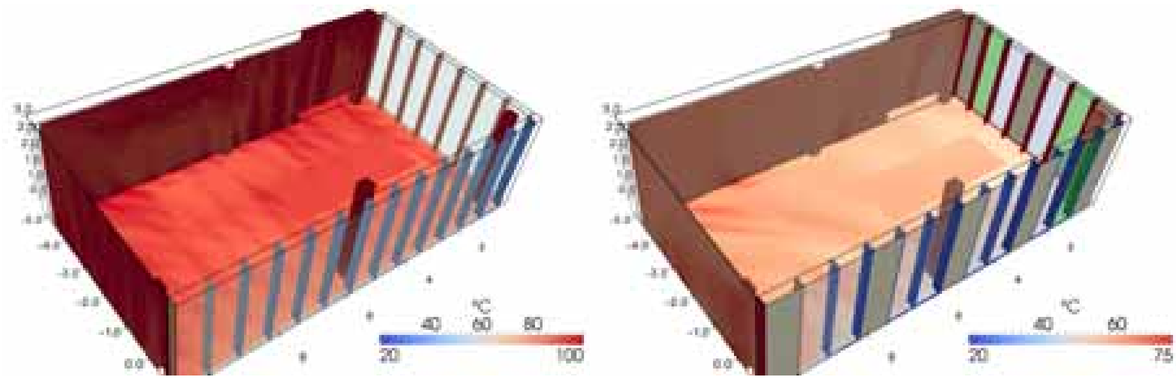

Figure 4: the temperature difference (relative to "standard" room temperature) at the floor and inner walls of the testing room, with the basic façade configuration (left) and the modified façade configuration (right).

As already mentioned, originating from the solar radiation, the inner vertical walls serve as a heat source for the indoor flow. As the room under investigation is assumed to be air-tight and without ventilation, the natural convection is the dominant flow effect. The established flow pattern can be analyzed from Fig.5, where the velocity vectors are show for three cut-planes. The irradiated walls are heating up the air in the wall vicinity giving rise to the natural convection plumes. The up-flow plumes are the strongest near the corners of the inner walls, then they are being deflected by the room ceiling creating a down-flow plume near the outer walls, and finally the convection cell is closed in the centre of the room through the flow near the room floor. If Fig.3, Fig.4 and Fig.5 are compared, it becomes clear that the established flow pattern is primarily dictated by the characteristic thermal field, which actually follows closely the solar irradiation pattern on the floor and inner walls.

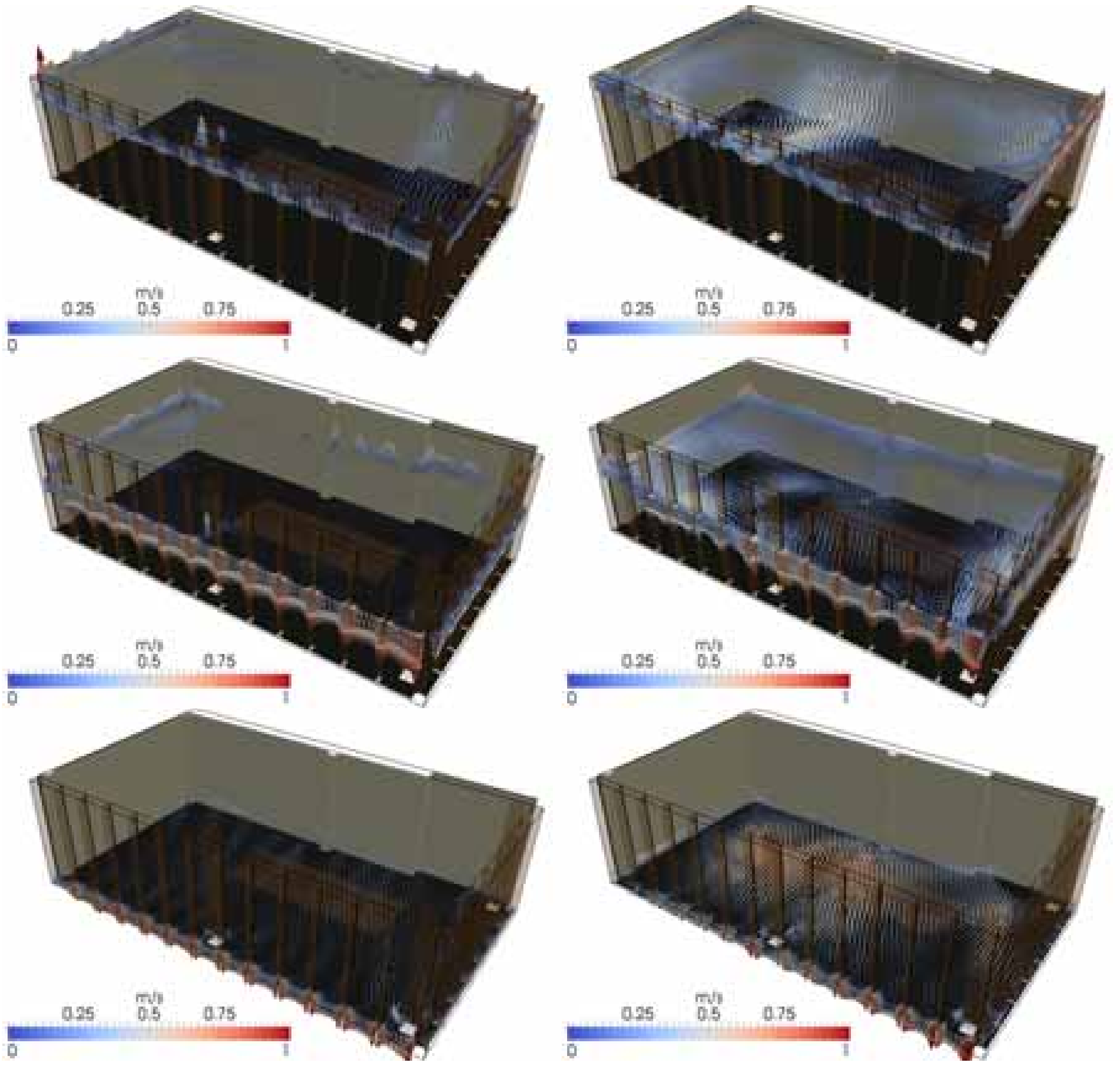

Figure 5: the velocity vectors in the horizontal cut-plane close to the ceiling (top), at the half-height (middle), and the floor (bottom) of the testing room, with the basic façade configuration (left) and the modified façade configuration (right).

There are two effects that need to be discussed by comparing the two façade configurations in the test room. Firstly, the obtained temperatures (Fig.4) are much higher for the basic façade configuration, primarily because the solar energy input here is much higher compared to the modified façade configuration (nearly half of the façade surface is opaque there). This is easy to inspect in Fig.3, which shows much lower values for the solar radiation heat flux, for the case when nearly half of the façade surface is opaque (compared to completely transparent case). Furthermore, it is interesting to note that the overall temperature level is relatively high, because the simulated room was assumed to be fully air-tight and without ventilation. Given that the room is very well insulated, the solar heating gives rise to relatively high temperatures.

And secondly, the obtained flow pattern is much more “regular” for basic façade configuration, compared to the “irregular” flow pattern obtained for the modified façade configuration (Fig.5). Namely, in the basic configuration the room is evenly irradiated through the entire façade, whereas in the modified case there are significant parts of the room that are not directly irradiated (and hence unevenly heated). This creates uneven distribution of the driving buoyancy force, and hence uneven flow pattern is established in the near-wall region. Note that the flow pattern is much more complex around the table, which has been introduced in the simulation of an empty room in order to make the flow situation more realistic.

5. Conclusion

This paper presented a novel approach for the solar radiation modelling, which is based on the concept of path-tracing. Using this concept the obstacles regarding the geometrical complexity of the simulated domain are strongly diminished, and the computational overload for introducing the radiation effects in the fluid flow simulation is significantly reduced. Furthermore, this method can easily be extended to include the frequency dependent material properties, as well as the multiple reflections.

In the analysis of the test room with two façade configurations it was shown that the path-tracing approach accounts for the solar radiation effects, such as transmission or absorption. Coupled with the CFD tool (here with FLUENT) this approach expands the applicability of the numerical fluid flow simulations on the problems in which solar radiation is dominant, as the interaction between the velocity field and the thermal field (including the contribution from the radiation) is directly enabled.

The results obtained using the coupled path-tracing – CFD simulation of the solar heating of the test room (air-tight room without ventilation, two different façade configurations analyzed), show the flow pattern characteristic for the indoor flows with dominant natural convection. The established natural convection cell is dictated by the thermal field which is originating from the solar irradiation pattern. This is clearly visible comparing the established flow patterns for two different façade configurations: as the irradiation patterns differ strongly, the corresponding flow characteristics are also different. The overall temperatures obtained are relatively high, as the room is assumed to be air-tight and without ventilation, but with very good insulation. Naturally, the difference between obtained room temperatures is observed for different façade configurations.

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